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(JAPAN TECHNOLOGY PROGRAM)

Nanofabrication Technology in Japan

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This directory was prepared in response to the Japanese Technical Literature Act of 1986. This Act requires the Secretary of Commerce to prepare annual reports regarding important Japanese scientific discoveries and technical innovations in such areas as computers, semiconductors, biotechnology, and robotics and manufacturing.

U.S. DEPARTMENT OF COMMERCE
Ronald H. Brown, Secretary

TECHNOLOGY ADMINISTRATION
Mary L. Good, Under Secretary for Technology

NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
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PREFACE

This report is written in partial satisfaction of the requirements of the Japanese Technical Literature Act of 1986, Public Law 99-382 (Aug. 14 1986). This law requires the Secretary of Commerce to prepare annual reports on the important scientific discoveries and technical innovations in certain important identified areas such as computers, semiconductors, biotechnology, robotics, and manufacturing. This report on Nanofabrication Technology in Japan is the result of a visit to corporate, government, and academic research facilities in the Tokyo, Tsukuba, and Sendai areas by Dr. John A. Dagata, a research scientist in the Precision Engineering Division, National Institute of Standards and Technology, Gaithersburg, Maryland. Eighteen laboratories were visited during March 3-20, 1993 in preparation for this report. This visit included the author's participation in the inaugural workshop of the Agency for Industrial Science and Technology's large-scale Atom Technology Project, held March 8-9 1993 in Tsukuba. For further information on any aspect of this report, please contact the author at:

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EXECUTIVE SUMMARY

This evaluation of nanofabrication technology research in Japan was prepared in response to the Japanese Technical Literature Act of 1986 wherein the Secretary of Commerce is required to prepare annual reports regarding important Japanese scientific discoveries and technical innovations in such areas as computers, semiconductors, biotechnology, robotics, and manufacturing. This report is the result of a visit to eighteen corporate, government, and academic research facilities in the Tokyo, Tsukuba, and Sendai areas during March 3-20, 1993 and the author's participation in the inaugural workshop of the Ministry of International Trade and Industry's (MITI's) large-scale Atom Technology Project (ATP), held March 8-9 1993 in Tsukuba.

This report presents detailed summaries of major research activities related to the refinement of advanced manufacturing processes and instrumentation in diverse fields such as microelectronics, optics, ultra-precision machining, as well as progress in fundamental nanometer-scale materials science research. The organization of public-sector research and development (R&D) in Japan is examined at length with particular emphasis on the evolving role of the MITI in fundamental research. Through its network of committees of academic, government, and corporate advisors, MITI has identified nanotechnology as a discipline for which its technical and organizational infrastructure is ideally suited. MITI's large-scale ATP program, with an announced budget of U.S.$ 210 M spread over ten years, will involve foreign and Japanese academic, government, and corporate elements in an ambitious effort in this emerging area.

The transformation of MITI is occurring in Japan just as U.S. funding agencies are re-evaluating their own missions, with much debate centering on the creation of effective technology transfer mechanisms. There may be opportunities for both the United States and Japan in this situation, as the goals of cooperative basic research and industrial competitiveness become bound together in the pursuit of nanotechnology. In particular, Japan has clearly identified its needs by recognizing international collaboration, involving both individual researchers and institutions, as an essential part of MITI's ATP structure. This project, as it evolves over the next decade, should be of great interest to policy makers, program managers, and researchers in the United States as it will yield valuable lessons about the long-term direction of the scientific enterprise in Japan.

My discussions with researchers in Japan were conducted with a sense of complete openness and my experience at each of the research laboratories described in this report indicates that Japanese researchers are quite eager to express their opinions and aspirations. These discussions revealed that there are several potential difficulties which MITI's ATP must avoid as it strives for international recognition in nanotechnology over the next decade: First, prior success with its large-scale industrial R&D projects does not necessarily ensure its success in promoting basic science, since cultivation of fundamental research is a very different matter. It is not entirely clear at this time how certain aspects of MITI's programs, such as traditionally rigid goal-setting and a lack of synthesis of research results, might interfere with opportunities for original thinking and self-motivation. Second, U.S.-Japan programs for postdoctoral study in Japan have not attracted enough candidates to fill the available positions in the past. The institutional links

which are being established within the ATP may improve this situation, but will require considerable time and effort on the part of Japanese researchers in order to make the ATP a truly international effort.

In summary, there is considerable activity in the area of nanofabrication technology in Japan. The public-sector funding mechanism in Japan, especially through MITI's network of academic, government, and corporate research advisors and its project-oriented R&D strategy, is in a unique position to recognize and contribute to the fundamental knowledge base of this emerging discipline. Careful attention to progress made by programs such as MITI's ATP over the next decade is likely to provide valuable insight into how nanotechnology research can be effectively coupled to advanced manufacturing in the next century.

ABSTRACT

This report describes the organization of current major research activities related to nanofabrication technology now underway at corporate, government, and academic research facilities in Japan. Nanofabrication technology refers to an emerging discipline which integrates the refinement of advanced manufacturing processes and instrumentation in diverse fields such as microelectronics, optics, and ultra-precision machining with systematic and fundamental progress in materials science and, in particular, the routine production, manipulation, and characterization of surface and interface properties with atomic, or near-atomic, precision. Much of this progress can be linked directly to the recent availability of a whole range of novel surface-sensitive techniques such as scanning tunneling microscopy and molecular beam epitaxy. Recent events indicate the R&D community in Japan has recognized that a broadly integrated national nanofabrication technology research program will be essential for leading-edge manufacturing in the next century. The implications of this commitment to long-range nanoscale science and technology for future manufacturing will be discussed in detail.

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TABLE I. LIST OF ABBREVIATIONS USED IN THIS REPORT

AFM	Atomic Force Microscopy
AIST	Agency for Industrial Science and Technology
ALE	Atomic Layer Epitaxy
AMMTRA	Advanced Materials Processing and Machining Research Association
ATP	Atom Technology Project
ATP	Advanced Technology Program
CMM	Coordinate Measuring Machine
ETL	Electrotechnical Laboratory
ERATO	Exploratory Research for Advanced Technology
IMS	Institute for Materials Science (Tohoku University)
MBE	Molecular Beam Epitaxy
MITI	Ministry of International Trade and Industry
MLE	Molecular Layer Epitaxy
MOE	Ministry of Education
MOP	Ministry of Posts
NAIR	National Institute of Advanced Interdisciplinary Research
NEDO	New Energy and Industrial Technology Development Organization
NRLM	National Research Laboratory of Metrology
OTL	Optoelectronics Technology Research Laboratory
OTRC	Optoelectronics Technology Research Corporation
QFD	Quantum Functional Device
R&D	Research and Development
REM	Reflection Electron Microscopy
RHEED	Reflection High Energy Electron Diffraction
RMS	Root-Mean-Square
SCR	Super Clean Room Facility (Tohoku University)
SEM	Scanning Electron Microscopy
SRI	Semiconductor Research Institute (Tohoku University)
STA	Science and Technology Agency
STM	Scanning Tunneling Microscopy
TEM	Transmission Electron Microscopy
ULSI	Ultra-Large-Scale Integration

I. INTRODUCTION

A. What is Nanofabrication Technology?

Advanced manufacturing techniques enable an increasingly wide range of critically dimensioned mechanical, electronic, and optical components to be employed in commercially available products. These components have dimensions specified to well below 100 nm and, in certain cases, dimensional accuracies below 10 nm are required. Future generations of fiber-optic and wireless communications, data storage, integrated sensor applications, and computer electronics, will all rely heavily on such techniques.

The fabrication of nanometer structures requires careful selection of local chemical and physical conditions and monitoring in real time during the manufacturing process for the resulting device components to function properly. Furthermore, maintaining the desired electrical or structural properties of these critical structures during the completion of subsequent processing steps is essential. This level of control demands that new cooperative strategies for integrating long-term materials research and development (R&D) into manufacturing must evolve in order for nanometer-scale control to be realized. The term nanofabrication technology, or nanotechnology, as used here, refers, not only to the discovery of the tools and processes required for these tasks, but to the overall strategy which allows them to be implemented effectively into the manufacturing environment.

Tools and processes which are capable of routinely producing functional nanometer-sized structures consisting of only a few hundred or thousand atoms are limited at the present time [1]. Real-time characterization of such nanostructures is equally limited. A few examples of the most promising techniques for the control of materials systems currently being explored as part of this effort will serve to illustrate the range of activity: Layer-by-layer growth or etching of ordered surfaces of silicon, gallium arsenide, and other compound semiconductors using or stimulating the reactivity of surface atoms, e.g., molecular layer epitaxy and digital etching; scanning tunneling microscope-based techniques for imaging and manipulating single atoms and clusters on single-crystal silicon and metal surfaces; and, nanometer-scale pattern generation in resist by electron-beam and focused ion-beam lithography.

There will be much to learn from the technical contributions of Japan's researchers in the field of nanotechnology over the next decade. However, it is imperative that we recognize and follow the organizational developments that are taking place there as well. The need for sophisticated and expensive instrumentation, essential for carrying out meaningful work in this area, means that the traditional distinction between fundamental and applied research is becoming somewhat less clear, and that facilities where top-notch work can be performed will be limited. There are serious questions about how generic, or transferable, much of the more fundamental results will be.

The evolution of an effective R&D strategy for nanotechnology and the effective integration of these tools and processes into real-world manufacturing processes, will require careful policy

consideration. How this work is to be funded, how programs are to be managed, and who is to benefit from public-funded R&D are issues that will largely determine the ultimate success of the Japan and U.S. nanofabrication technology efforts.

B. Itinerary

The itinerary for this trip, summarized in TABLE II, evolved from my prior contacts with Japanese researchers, aided by the many extremely helpful suggestions of Dr. Hiroshi Tokumoto of the National Institute of Advanced Interdisciplinary Research (NAIR), Dr. Nobuhiro Tsuda of the National Research Laboratory of Metrology (NRLM), Dr. Victor Rehn of the U.S. Office of Naval Research-Asian Office (ONR-AO), and Dr. Larry Nagahara of the University of Tokyo. During the planning stage of this trip, December 1992 - February 1993, Dr. Rehn and Dr. Larry Weber of the U.S. National Science Foundation Tokyo Office (NSF-Tokyo) published reports on the ERATO projects[2] and on Nanofabrication Research in Japan[3], respectively. Access to these reports during this period made my task of selecting representative programs considerably easier. The present report is intended to complement these very useful summaries; here, I have tried to give a more personal emphasis to this subject based on my perspective as an active researcher in the field.

The material presented in this report was obtained through personal discussions with project leaders and researchers at eighteen corporate, government, and academic research laboratories in the Tokyo, Tsukuba, and Sendai areas during a 2 1/2-week period in March 1993. Detailed report summaries for individual laboratory visits are arranged in Section II according to the primary source of funding support for the project. At the beginning of each report summary, I have listed the names of the researchers with whom I held substantive discussions and the main topics which were discussed. Every laboratory visit was made through, and arranged by, a personal request to a specific researcher at the designated facility.

During this visit I had the opportunity to participate in the inaugural workshop of the Agency for Industrial Science and Technology's Atom Technology Project (ATP) at the National Institute of Advanced Interdisciplinary Research (NAIR) in Tsukuba. This participation, arranged by Dr. Tokumoto, enhanced the present report because it allowed me to engage in many additional discussions with researchers from institutions located in areas of Japan which I could not visit because of time constraints.

I wish to emphasize that these discussions were conducted with a sense of complete openness. My experience at each of the research laboratories described in this report indicates that Japanese researchers are quite eager to express their opinions and aspirations. Undoubtedly, this kind of personal exchange was made all the easier by a sharing of common interests between active researchers.

C. Scope of This Report

This report is intended to serve several purposes: First, it provides a detailed technical

TABLE II. ITINERARY

March 3.	Arrive Tokyo
March 4.	Office of Naval Research, Asian Office National Science Foundation, Tokyo Office Nikon Corporation
March 5.	University of Tokyo
March 7.	Travel to Tsukuba
March 8-9.	National Institute of Advanced Interdisciplinary Research
March 10.	National Research Laboratory of Metrology Electrotechnical Laboratory NEC Corporation
March 11.	Optoelectronics Technology Research Laboratory Aono Atomcraft Project
March 12.	Travel to Sendai Institute for Materials Science, Tohoku University
March 13.	Itaya Electrochemiscopy Project
March 15.	Super Clean Room Facility, Tohoku University Nishizawa Terahertz Project Semiconductor Research Institute, Tohoku University Travel to Tokyo
March 16.	JEOL Ltd. Hitachi Central Research Laboratories
March 17.	NTT Laboratories
March 18.	Canon Inc. Nippon-Motorola R&D Center
March 19.	RIKEN
March 20.	Leave Tokyo

summary of research activity in nanofabrication technology which is underway currently at major facilities in Japan. Major examples of this activity are described in Section II. Taken as a whole, these efforts have generated considerable recent interest within the U.S. scientific community. Many articles and reports have already appeared in specialized journals, as well as in the popular scientific press [2-5]. What is striking to many researchers and program managers, even long-time supporters of nanotechnology efforts in the United States, is the apparently firm commitment of Japan's industrial sector to support a sustained, basic research effort in this field.

Second, this report presents a concise description of public- sector R&D funding in Japan. How research is organized in Japan and, more specifically, how it has evolved in recent years is described in Section III. An understanding of this organization can yield clues as to why the Japanese R&D community has been so swift in recognizing the potential of nanotechnology.

Finally, it is important to understand how this infrastructure may impact on closely related issues, such as Japan's desire to play a leading role in international science. This point is considered in Section IV. It is clear that nanotechnology represents an area in which Japanese researchers feel that they can make the most significant contribution to the international scientific community in the coming years. Success in this area will depend to a considerable extent on establishing more effective relationships with U.S. and other scientists around the world.

II. INDIVIDUAL LABORATORY REPORTS

Because of the complex relationship which exists between government and industry in Japan, a brief explanation of how public- and private-sector funding should be distinguished in the reading of this report is in order.

It is easier to begin by first describing what constitutes the private-sector R&D in Japan. In this case, the direction of major research programs at leading corporations is fairly similar to the pattern established in the U.S. In fact, at the time many of the more established corporate R&D centers were initially founded, they were patterned on highly regarded corporate research centers in the U.S. such as Bell Laboratories. Until rather recently these efforts were focused almost exclusively on R&D that was judged to have a clear technological impact on the corporate product line. The tremendous success of Japanese companies in the global marketplace has led to a fairly significant expansion of in-house R&D to include more exploratory, or fundamental research, at many if not, all major corporate research centers.

The funding and direction of public-sector R&D in Japan, by contrast, is significantly different from that in the U.S. The most notable differences lie in: (1) The involvement of Japan's major corporations as advisors and contributors to, as well as beneficiaries of, public-sector research. The contributions that the corporations typically make to this effort include research facilities and personnel, in addition to direct financial support for specific projects; and (2) The reliance on a system of usually narrowly focused, fixed-term research projects which are disbanded upon completion of the project.

There are three main sources of public-sector R&D in Japan: the Ministry of International Trade and Industry (MITI), the Ministry of Education (MOE), and the Science and Technology Agency (STA). I will emphasize the potential impact of MITI's involvement in nanotechnology in later sections of this report because of its close involvement in advancing Japan's manufacturing technology. Each of these agencies contributes in its own characteristic and very substantial way to the shaping of the overall directions of science and technology in Japan. Quite likely, the potential for Japan's success in nanotechnology is embedded within the unique cooperative organization of its R&D effort.

The impressions and observations which support this viewpoint are presented in Section III. They are based on the many hours I spent discussing organizational, as well as technical, aspects of each project with the researchers mentioned in the individual reports. More detailed information about specific projects or research results is available by contacting the author of this report.

A. PUBLIC-SECTOR RESEARCH AND DEVELOPMENT

1. Projects of the Ministry of International Trade and Industry

(a) The AMMTRA Project

Facilities Visited:
National Research Laboratory of Metrology, Tsukuba
Canon Inc., Tokyo
Nikon Corporation, Tokyo

Researchers:
Drs. H. Yamada, M. Tanaka, H. Matsumoto, and N. Tsuda (NRLM)
M. Ando, M. Negishi, and M. Ohtsuka (Canon)
Drs. K. Iizuka, T. Fujii, Fukutomi, M. Suzuki, and H. Ohsawa (Nikon)

Discussion Topics:
AMMTRA Organization
AFM/STM Instrumentation with Integrated Metrology
Two-color Laser Interferometry
Ultra-smooth Polishing for Large Optics
Measurement System for Cylindrical Optics

SUMMARY

The purpose of my visit to the National Research Laboratory of Metrology (NRLM) in Tsukuba was to learn about MITI's Advanced Materials and Machining Technology Research Project (AMMTRA). This is an example of an existing Large-scale National R&D project. I was interested in understanding government and industry participation in these projects, especially in terms of how the technical and information output is actually generated and shared among the corporate members of the R&D association. I had the chance to meet with Drs. H. Yamada, M. Tanaka, H. Matsumoto, and N. Tsuda who have been involved in metrology support for the AMMTRA project.

AMMTRA is an eight-year project, in its final year of operation. The project has been broken down into three main R&D directions: (1) excimer-laser processing technology, (2) ion-beam processing technology, and (3) ultra-precision machining technology, with provisions for supporting technology. Laser and ion-beam processing have potential advantages for manufacturing critically dimensioned parts. The current technical challenges are to increase the energy or power density of the sources and to produce efficient focusing and beam shaping optics systems so that rapid and reliable processing can be achieved.

The activities associated with the AMMTRA project at NRLM include ultra-precision

measurement and evaluation techniques for x-ray mirrors and other machined components which require control of the surface roughness of the substrates well into the nanometer-scale regime. I was quite impressed with several of the techniques that were being explored, including a novel optical interferometric straightness test facility which employs a novel, three-point detection method. This instrument had been built by Dr. Tsuda and his colleagues. A two-color laser interferometry system which compensates for the refractive index of air and the penetration of light into the sample surface, designed and built by Dr. Matsumoto, overcomes significant nanometer-scale metrology problems. I also observed several STM and atomic force microscope (AFM) systems using folded parallel springs for surface roughness measurements, built by Drs. Tsuda and Yamada. I also found the highly compact (30 mm) combined magnetic and piezoelectric positioners with integrated optical interferometry, designed by Dr. Tanaka, to be particularly noteworthy. More recently, Dr. Yamada has built an ultrahigh vacuum (UHV) AFM system for studying organic adsorbates. An understanding of the detailed interactions which occur during AFM imaging, particularly with organic and biological samples, has proven to more complex than was at first thought. The ability to perform experiments under controlled conditions requires such a system. Dr. Yamada has recently become a member of the Atom Technology Project.

In addition to my visit to NRLM, I met also with corporate researchers at Nikon and Canon. These companies have been major participants in the AMMTRA R&D Association, which consists of over twenty member companies. Canon, for example, has been responsible for building and operating an ultra-precision grinding and measurement instrument. Nikon and NRLM have been involved in developing measurement and evaluation technology for excimer laser optics using scanned probe methods.

I visited the Canon research laboratory in Ohta to learn about their work related to the MITI's large-scale AMMTRA project, now in its final year. I discussed this project with M. Ando, M. Negishi, and M. Ohtsuka on two systems which were constructed in fulfillment of that work. The first was a system for polishing large diameter optics for ultraviolet and x-ray applications which included a polishing station and integrated profile measuring system (CMM) which was described by Mr. Ando and Mr. Negishi. The aim of the project was to use standard substrate materials, e.g., quartz and SiC, and processes, CeO_2 fluids, and techniques. The goals of 80-nm figure accuracy and 0.2-nm RMS surface roughness (as measured by the CMM) for the project have been achieved for 100-mm diameter planar optics. Work on achieving these results for target 500-mm diameter optical parts is underway.

It is worth noting that the cost, U.S. $ 3M, and effort required for the construction of this instrument is considerable. I was impressed that this instrument could be built, and be well on its way towards meeting its target specifications in the time allotted. Clearly the prior expertise of the company in the design and execution of these instruments, along with in-house teams of software and other technical support makes this possible. This is an example where a clearly defined requirement of the overall project, i.e., the production technology for large-diameter precision optical substrates, could best be achieved in terms of time and money through corporate resources.

The second instrument which I was shown by Mr. Ohtsuka was a surface-profile measuring system for cylindrical mirrors. The development of this instrument was supported partially by the AMMTRA project. The production of one-meter long cylindrical mirrors with a radius of curvature of 100-m are important for synchrotron x-ray optics and this work involved collaboration with university researchers as well. Researchers at Canon have approached this difficult measurement problem by using a two-dimensional heterodyne phase technique in which a null pattern is generated optically. Currently, the system is capable of measuring surface profiles for mirrors consisting of 700-mm long sectors with 3-nm root-mean-square (RMS) repeatability in the phase data.

I visited Nikon corporate offices in Tokyo to discuss Nikon's involvement in MITI's AMMTRA project with Dr. K. Iizuka, director of corporate R&D strategy, after which we traveled by train to Nikon's Ohi plant in the Shinagawa area of Tokyo.

At Ohi, the four scanned probe systems under development for AMMTRA were discussed with Drs. T. Fujii, Fukutomi, M. Suzuki, and H. Ohsawa. Two of these systems combined co-axial optical/probe designs, one of which employed an iodine-stabilized laser interferometry system. This latter system was still under construction; the goal was an AFM instrument which could be combined with an optical fluorescence detection scheme in both episcopic and transmission modes. Much of the effort going into this system was devoted to automating the difficult co-alignment problems of the microscopies. The researchers seem well on their way to handling these problems and a powerful new tool, particularly for biological applications should emerge.

A third system was based on the scanning near-field optical microscope concept where a glass pipette, drawn down to a diameter of 20 nm induces or detects the evanescent optical field at a sample surface. Excitation sources included laser diode, He-Ne, and, most interestingly, a Cd laser. The idea was that simultaneous, 3-color (RBG) sample imaging might be possible. Again, these efforts point toward coupling well-understood optical concepts to high-lateral resolution probe microscopy.

It is interesting to note that this work was being carried out in the basement of a production plant where considerable electromagnetic (EM) and acoustic interference was present. In addition, the plant is located on a very active sand bed. I was impressed with the specially built, EM-shielded rooms and active vibration isolation systems that were employed. The isolation system used a high-sensitivity accelerometer which was developed in-house. This led to an impressive 30-dB attenuation of the main (11 Hz) tidal resonance experienced at this location. Confronting such realistic environmental challenges is an important aspect of engineering considerations for nanotechnology.

Traditionally, R&D association members contribute the major portion of the facilities and personnel needed to carry out the technical aspects of these projects. The subprojects are carried out at the corporate facilities and usually no effort is made at or near completion of the program to integrate the subprojects.

(b) The Quantum Functional Device Project

Facilities Visited:
Electrotechnical Laboratory, Tsukuba
Nippon-Motorola, Tokyo

Researchers:
Dr. K. Sakamoto (QFD Project Leader, ETL)
Dr. M. Tomozane (Nippon-Motorola)

Topics Discussed:
Organization of QFD Project
Exploratory Device Concepts

SUMMARY

I met with Dr. K. Sakamoto of the Electrotechnical Laboratory (ETL) in Tsukuba. He is project leader of MITI's new Future Technologies R&D project on Quantum Functional Devices (QFD). This program is in the second year of its ten-year run. A noteworthy aspect of the QFD project is that it is, in effect, the continuation of an earlier MITI project, the Future Electron Device project, which ran from 1981-1991. The R&D association, called the Future Electron Device Association and consisting of five of the largest Japanese electronics firms, has remained essentially intact for this second ten-year effort, with the addition last year of Nippon-Motorola.

The private industries, i.e., R&D association members, which benefit from these projects are active in the planning committees. Their cooperation over time on a number of the these projects generally ensures the relevance of MITI's programs. The structure of MITI projects has evolved as a result of the long-term, often uncomfortable, relationships developed among the government agencies and the corporations. The primary role of the project leader, who must come from the government, is to serve as a neutral coordinator for the technical activities, which occur mainly at corporate facilities. Typically, support R&D is carried out at government labs such as ETL, or sometimes subcontracted out to universities.

Each of QFD association members is exploring a novel device approach: Tunneling control functional device (NEC), quantized band coupling multifunctional device (Motorola), resonant electron transfer functional device (Matsushita), quantized energy level memory device (Fujitsu), coupled quantum dot device (Sony), and quantum wave structure functional device (Hitachi). Dr. Sakamoto, the project leader, is investigating the effects of strain and surfactant on the growth of silicon-germanium superlattices for possible device applications of these structures at ETL. It seems clear that these are all free-standing, exploratory efforts and that this project is not expected necessarily to converge on some final device concepts, but will provide a valuable information base to support future technology selection.

Nippon-Motorola is a subsidiary of the major U.S. electronics company. As a member of the Atom Technology Project (ATP) and FED R&D associations, this company has a unique perspective on corporate interactions within the MITI's R&D association structure. I spoke with Dr. M. Tomozane at Nippon-Motorola offices in Shinagawa. At this time Motorola's R&D effort in Japan is insignificant, although there are production facilities, the largest located in Tsukuba. Therefore, Motorola's contribution to the QFD project, quantum multi-function transistors based on the concept of interband tunneling in double barrier tunneling diodes, is being performed in the United States.

Dr. Tomozane emphasized that their involvement in these associations was an important way for their presence in Japan to be recognized by government agencies and other corporations. This is similar to the response of other U.S. companies to a recent NSF survey. He also mentioned that while he felt that Motorola was treated as true member of the association by the other companies, he felt that Motorola enjoyed freer access to other members corporate research facilities than did other Japanese corporations. Evidently, Motorola was not viewed as a direct competitor under these circumstances. Their commitment to the QFD program led to an early MITI invitation to join the ATP and assist in the organization of its R&D association. This experience suggests that a commitment to fundamental R&D interactions on the part of U.S. corporations may be good strategy for furthering relationships in Japan.

(c) Optoelectronics Technology Research Project

Facility Visited:
Optoelectronics Technology Research Laboratory, Tsukuba

Researchers:
Dr. Y. Katayama (OTL research director), Drs. T. Ishikawa, F. Osaka, M. Tamura, J. Palmer-Fortune, and Y. Morishita.

Topics Discussed:
Organization of OTL
in-situ Processing of GaAs
Heteroepitaxial Growth
STM, μ-RHEED, MBE, TEM, Electron-beam Lithography

SUMMARY

The Optoelectronics Technology Research Laboratory (OTL) in Tsukuba represents a change in how MITI has organized joint research projects. As in the case of QFD, the OTL was established as a result of experience with previous programs in VLSI and optoelectronics. The problem arises from the fact that the existing program structure, as described in the AMMTRA and QFD reports, made further research integration difficult because of corporate resistance to the idea of allowing competitors into their facilities. The solution was to build a common research facility to which researchers from the R&D association members would transfer for the

duration of the project.

The scope of the common research facility is somewhat narrowly focused on process research for compound semiconductors, with device research still handled at member's labs. Another crucial difference in this strategy compared to more traditional MITI projects is that the research to be performed at OTL was not prescribed at the onset of the project, but management and researchers at OTL were given the responsibility for determining its direction. This is a clear indication that MITI had recognized that intensive research into materials processing technology and diagnostics for opto-electronic integrated circuit (OEIC) applications would require greater independence and self-motivation than had been allowed previously.

I met with Dr. Y. Katayama, research director of OTL, and with Drs. T. Ishikawa, F. Osaka, M. Tamura, J. Palmer-Fortune, and Y. Morishita. Dr. Katayama, for instance, joined OTL from Hitachi and Dr. Palmer-Fortune is a U.S. postdoctoral researcher at OTL. I discussed compound semiconductor heteroepitaxy growth studies with Drs. Tamura and Palmer-Fortune who are using transmission electron microscopy (TEM) and ion scattering to diagnose growth problems associated with the formation of defects arising from lattice mismatch between the materials.

Real-time diagnostics for the epitaxial growth of compound semiconductors is an extremely important area of current research. This is because of the difficulties involved with the growth of low-crystalline-defect material. Many of these defects are initiated at localized sub-micron-sized defects. The μ-RHEED technique is a method being used by Dr. Morishita which combines the familiar reflection high-energy electron diffraction (RHEED) technique with a localized diffraction spot detector in order to produce images of how such defects behave under different processing parameters. This is a very promising technique which is likely to become widespread in the molecular beam epitaxy (MBE) community. The STM offers atomic resolution and Dr. Osaka discussed his results of studying the electronic effects at cleaved InGaAs/InP heterostructures.

An issue that has generated intense interest recently in the area of nanofabrication technology is in-situ processing, the development of integrated processing techniques whereby complex, multi-layer optoelectronically active structures are grown and patterned under ultra-high vacuum conditions, thus preserving these desired properties. OTL has been one of the pioneers of this concept. I was briefed by Dr. Ishikawa on the approach used by OTL consisting of the following steps: (1) MBE to prepare highly perfect gallium arsenide surfaces, (2) controlled surface photoxidation to form a nonreactive mask layer, (3) mask patterning of the oxide layer by electron-beam (e-beam) -induced Cl_2 etching, and (4) chlorine etching of the e-beam exposed surface to remove layers of the semiconductor material in a precise fashion. The compatibility issues which arise when such an array of processing systems is coupled are quite complex. The expense of building and operating systems such as this to investigate these issues will certainly limit their number until the commercial potential of in-situ processing can be estimated better.

I left OTL impressed by the cohesiveness of the program and the high degree of interaction

which had been established among the researchers. Again, I must point out that these researchers are on assignment from their corporate labs. The project is scheduled to conclude an eight-year term in 1994.

(d) The Atom Technology Project

Facility Visited:
National Institute of Advanced Interdisciplinary Research, Tsukuba

Researchers:
Drs. K. Tanaka, H. Tokumoto, and M. Ichikawa

Topics Discussed:
Organization of ATP
First NAIR Workhop on Atom Manipulation
High-resolution STM
Reflection Electron Microscopy

SUMMARY

The National Institute for Advanced Interdisciplinary Research (NAIR) in Tsukuba was established earlier this year. The Institute will serve as the home of the Atom Technology Project (ATP) which began this year as well. The ATP has created considerable interest in the US because of the long-range objectives of this project and the budget, approximately US$ 210M over ten years. The overall goal of the project is to provide the generic technology which MITI believes will be essential for leadership in the electronics, chemical, and biotechnology fields in coming decades.

The ATP is extraordinary in the sense that its intention is to unite advanced manufacturing concepts with nanoscience and industrial policy with funding for fundamental research, it reveals much about where Japan sees itself today and where it will go. Section III of this report examines this point more fully.

I participated as an invited speaker in the inaugural NAIR Workshop on Atomic Manipulation held in Tsukuba on March 8-9 1993. The meeting consisted of three sessions devoted to the main topic areas of the ATP: (1) laser cooling of neutral atoms and ions as a technique for the manipulation of gas phase species, (2) STM imaging and modification of adsorbed species on surfaces, and, (3) theoretical approaches for modeling such processes. The agenda for the meeting appears in TABLE III. It is interesting that this basic formula appeared as early as 1989 in the technical proposal for the project.

I was able to discuss organizational and thematic aspects of the ATP with three of the seven group leaders, Drs. K. Tanaka, H. Tokumoto, and M. Ichikawa. Since the actual NAIR

TABLE III. Agenda for the Inaugural Workshop of the Atom Technology Project, NAIR Tsukuba March 8-9 1993.

Session 1. Manipulation in 3-D Space

S. Chu (Stanford U)	Manipulation of Atoms and Particles with Laser Light
F. Shimizu (U Tokyo)	Manipulation of Laser-cooled Neutral Atoms
S. Urabe (Comm Res Lab)	Trapping of Ions and Laser Cooling
H. Hori (Yamanishi Univ)	Nanometric Resolution Photon STM and Single Atom Trapping

Session 2. Theoretical Study

I. Stich (Cambridge U)	First Principles Studies of Semiconductor Surfaces: Reconstruction and Dynamics of Dissociative Chemisorption
Y. Morikawa (U of Tokyo)	First Principles Molecular Dynamics Study of Alkali-Metal Adsorption on Si(001) Surface
H. Nakatsuji (Kyoto U)	Quantum Chemistry for Surface-Molecule Interacting Systems
M. Hirao (Hitachi)	Electronic Structure and Optical Properties of of Hydrogenated Si Clusters
S. Itoh (Toshiba)	Gradient-corrected Spin-density Functional Approach to Antiferromagnetic Semiconductor $MnTe_2$
K. Kobayashi (NIRIM)	First-principles Molecular Dynamics Study of the Structural Stability of Silica
H. Nagara (Osaka Univ)	Molecular Orientation in Compressed Hydrogen Studied by First-principles Molecular Dynamics

Session 3. Atomic Observation and Manipulation by Scanning Probe

D. Eigler (IBM)	Atomic Manipulation with Scanning Tunneling Microscope
M. Tsukada (Univ Tokyo)	Mechanism of STM and Atom Manipulation based on First-principles Electronic State Theory
J. A. Dagata (NIST)	Integration of STM-based Nanofabrication and Characterization with Electronic Device Processing
K. Itaya (Tohoku Univ)	Electrochemical Interfaces
S. Morita (Hiroshima Univ)	Contact Electrification and its Dissipation on thin Si Oxide
A. Ikai (Tokyo Inst of Tech)	AFM/STM of Biostructures at Nanometer Scale
M. Hara (RIKEN)	AFM/STM Imaging of Organic Molecular Systems

laboratory facilities will not be completed for at least another year, it is impossible to comment on specific technical matters. However, the past achievements of the group leaders in their respective areas indicates that NAIR will cover a considerable range of nanotechnology research.

The group leaders, their affiliations, and the main focus of their research are:

Tokumoto	(ETL,NAIR)	Scanned Probe Techniques
Ichikawa	(Hitachi)	Focused Beam/Atomic Manipulation Microscope
Okada	(Olympus)	Multi-sensing/multi-functional Probes
Kanayama	(ETL,NAIR)	Nanocrystals, Self-assembly
Ozeki	(Fujitsu)	in-situ III-V Dynamical Characterization
Tanaka	(ETL, NAIR)	Process Diagnostics
Terakura	(Univ. of Tokyo)	Theory

I will mention the work of Drs. Tokumoto and Ichikawa to illustrate the scientific and technical foundation of the ATP. Dr. Tokumoto and his colleagues at ETL have used STM to obtain information about the stability and motion of steps and domains of reconstruction on silicon surfaces at elevated temperatures. This work was carried out using a JEOL 4500VT variable-temperature STM, in collaboration with JEOL personnel. (This microscope is described in more detail below.) Another effort of his group has been the systematic STM study of hydrogen termination on silicon surfaces. They obtained for, the first time, atomic resolution images of both $-SiH_3$ and $-SiH$ terminated surfaces and correlated their appearance with the processing conditions. This information is not only of use for future nanofabrication technology but is relevant for silicon ultra-large scale integration (ULSI) where microroughness must be controlled on the nanometer-scale level. (See also the section on the Super Clean Room facility at Tohoku University.) Major themes of Dr. Tokumoto's effort at NAIR include the development ultra-high precision, low-temperature, multi-functional, and electrochemical probe techniques to probe individual atoms and their exact interactions with the surface.

Dr. Ichikawa has contributed substantially to the understanding of silicon MBE by developing highly advanced electron microprobe instruments at Hitachi's Central Research Labs. He has used the μ-RHEED and reflection electron microscopy (REM) techniques as in-situ probes to image current-induced step flow on silicon surfaces during growth. The major themes of Dr. Ichikawa's group are characterization methods combining beam techniques, such as REM, with STM for manipulation and thin film techniques for growth.

Dr. E. Maruyama, project leader for the ATP Research Body, has retired from Hitachi to take this position. This was required in order to avoid the conflicts within the ATP R&D association. Currently there are about fifty members of the ATP association, with five largest Japanese electronics firms, i.e., Hitachi, Fujitsu, Matsushita, NEC, and Matsushita, forming a first tier, and smaller companies forming second and third levels. This structure establishes a common research facility, NAIR, following MITI's innovative experience with the OTL project,

described above. In addition, it implements a new element, the explicit involvement of foreign research organizations. In order to understand why MITI should seek out such collaborations, it is useful to look at the projects of the Science and Technology Agency.

2. Science and Technology Agency

(a) Frontier Research Programs (RIKEN)

Facility Visited:
RIKEN, Saitama

Researchers:
Drs. W. Knoll, H. Sasabe, and M. Hara

Topics Discussed:
International Research Climate at RIKEN
STM/AFM Imaging of Ordered Organic Molecular Films
Heteroepitaxy
Atomic Layer Epitaxy
Digital Etching

SUMMARY

RIKEN, The Institute of Physics and Chemistry, is a Science and Technology Agency (STA) research facility in Saitama which supports a broad range of basic research in the physical and biological sciences. The Frontier Research Program was initiated in 1986 to carry out long-term research in three areas: Bio-homeostasis, Brain Mechanism of Mind and Behavior, and Materials Research. The sense of place of this research facility was perhaps closest to that of a U.S. university research lab, and I was struck by this at the time.

As I learned later during conversations with Drs. W. Knoll and H. Sasabe who head the Exotic Nano-materials and Nano-photonics Laboratories, respectively, this effort on the part of the STA to create a more "international" climate for its research facilities is an important element of RIKEN's approach to fundamental research. The most telling signs were the lack of formality, the presence of a large number of international visiting scientists, and an almost equal gender ratio among the researchers and technical staff. The policy of making research in Japan more accessible to foreign researchers has become a key element in the STA's strategy for Japan to play a greater role in the international science community. Dr. Knoll provided a unique perspective on this situation, since his comments reflected both his administrative and personal experiences. The degree to which other Japanese research efforts, such as MITI's ATP, can succeed in fostering an international research climate is crucial. I discuss this point in more detail in Section III.

I visited the Laboratory for Exotic Nano-material with Dr. M. Hara. This group has made considerable progress in developing reliable procedures for studying ordered organic molecular assemblies on surfaces using scanned probe techniques. The emphasis on reliability is crucial because many of the difficulties that researchers in this field have encountered in past had to do with properly immobilizing the material onto the substrate so that the adsorbate structure is not disturbed during imaging. Proper attention to surface cleaniness, chemical termination, and control during preparation and imaging is an essential first step toward realizing the technological potentials of ordered biological and organic thin film systems.

The group is using wet chemical Langmuir-Blodgett and organic molecular beam epitaxial (OMBE) techniques and have looked at organic systems such as an ordered layer of ferritin bound to an anchoring monolayer consisting of a charged protein. They have performed considerable systematic work with liquid crystals. Their work was carried out with Nanoscope II STMs, and they had developed recently a UHV STM which is to be used in system that includes a glove box for sample preparation and transfer system to an OMBE growth chamber.

The OMBE work particularly appears to have enormous potential when considered within the extreme heteroepitaxy framework of Prof. A. Koma of the University of Tokyo, described below. In this case, they were the first to demonstrate the possibility of obtaining ordered monolayers of copper phthalocyanines on MoS_2. Indeed, I spoke about this to Dr. Hara who noted that Prof. Koma is an advisor to the RIKEN program. Prof. Koma's group has subsequently begun their own investigations of the orientational dependence of phthalocyanines on various substrates and his group is pursuing a systematic understanding of these systems.

I also had the opportunity to visit the Laboratory for Nano-electronic Materials which is headed by Dr. Y. Aoyagi. Research into the preparation of precisely controlled III-V semiconductor structures using advanced growth and etching techniques and the use of this material in quantum-effect devices is being carried out at these facilities. Some examples of the very impressive research instruments which had been developed in this laboratory were a laser-assisted atomic layer epitaxy (ALE) system and an ion-beam/excimer-laser assisted digital etching system. In the ALE technique, the laser serves as an energy source to selectively dissociate adsorbed organometallic molecules on the surface, without breaking apart gas-phase molecules, which would otherwise lead to uncontrolled reactions. In the etching case, a pulsed, low energy ion-beam, used in conjunction with a shuttered Cl_2 gas source, can be computer-controlled so that sequential adsorption, dissociation, and reaction of chlorine radicals with surface atoms occurs. Since undissociated Cl_2 does not react with the surface atoms, layer-by-layer removal of the surface occurs. This latter techniques combines some of the elements used in the OTL in-situ processing facility.

The laboratory was equipped with commercial UHV STMs, including a JEOL high-temperature system, a Japanese product, and an Omicron STM system, a German product.

(b) ERATO Projects

(i) Aono Atomcraft Project

Facility Visited:
Aono Atomcraft Project, Tsukuba

Researchers:
Drs. M. Aono, F. Grey, E. Snyder, and M. Sawamura

Topics Discussed:
Atom Manipulation
STM Theory and Experiment
Electron Tunneling

SUMMARY

I discussed the Atomcraft project with Dr. M. Aono at RIKEN, having earlier visited the ERATO project facilities in Tsukuba where I met Drs. F. Grey, E. Snyder, and M. Sawamura. The Atomcraft project consists of three groups: a Basic Analysis group, a Structure Control group, and a Surface Measurement group. The distinctions are somewhat arbitrary, but there has been a fruitful joint theory-experimental component which has evolved during the course of this project. These efforts have focused on systematics of atom manipulation; specifically, they have investigated the field-induced modification of clean silicon surfaces in UHV. A number of other aspects of this project were well along, including experiments involving advanced tip preparation and characterization techniques. The group has reported experimental results recently which may lead to a better understanding of the imaging and electron tunneling through organic molecules adsorbed on surfaces. The project members were constructing several UHV STM systems for this project including a custom-built low-temperature STM system, and commercial STMs: an Omicron STM combined with field evaporation, a JEOL 4500VT variable-temperature STM, and a VG Instruments STM from the U.K.

The project is nearing completion of its five-year term in September 1994. Dr. Aono indicated that certain aspects of the Tsukuba effort would continue as part of a comprehensive proposal to RIKEN. He mentioned his interest in pursuing atomic manipulation further and in combining low-voltage (hyperthermal) ion scattering experiments with STM. This latter approach may make it possible to obtain informtion about the mass and binding energy of adsorbates on surfaces. He also expressed keen interest in techniques that would allow the STM tip to sense adsorbate-specific properties for chemical analysis.

ERATO projects are required by the STA to have international researchers as active participants. Drs. Grey (Canada) and Snyder (US) are foreign members of the project.

(ii) Itaya Electrochemiscopy Project

Facility Visited:
Itaya Project, Sendai

Researchers:
Prof. K. Itaya and Dr. T. Yamada

Topics Discussed:
Electrochemical STM
Liquid-solid Interfaces
Chemical Identification of Adsorbates on Surfaces

SUMMARY

During my conversation with Prof. K. Itaya at his ERATO laboratory in Sendai, he emphasized that there are certain clear distinctions between fundamental and applied research. He took great pride in expressing the importance he attached to looking at a problem with sufficient depth and independence so as to get a real intellectual understanding of the problem. His statement expresses what I sensed in the enthusiasm of others, that nanotechnology represents an opportunity for many in the Japanese research community, particularly those outside academia, to do so.

His point raises a challenging question for nanometer-scale research: Are the foundations of this discipline so established at this time to justify the intense efforts planned to explore its technological consequences? For example, development of scanned probe techniques slightly more than a decade ago has, without doubt, given substance to the dreams of nanotechnology. Even now, however, the subtle physical details of how the probe tip interacts with the sample surface under various conditions are just beginning to be understood.

Prof. Itaya outlined his ERATO project, which began its five-year run this year. The overall interest is the detailed study of liquid-solid interfaces. This project builds on his substantial and impressive work since 1986 in the area of electrochemical STM studies, primarily imaging metal and graphite electrodes in solution during electrochemical deposition of Ag, Cu, and oxidation reactions, and more recently, hydrogen-terminated silicon surfaces. He stressed the importance of coupling the STM capabilities with other surface sensitive techniques, and we discussed a UHV system under construction in his laboratory which would combine an Omicron STM microscope for surface imaging with raman spectroscopy in order to identify key moecular species at the interface. I also had the chance to speak with Dr. T. Yamada, the key researcher involved in this experiment.

Coupling techniques in this manner is an essential strategy for obtaining information about complex interfaces and to explore the potential of the STM for chemical identification purposes. The use of the STM for chemical identification of atomic or molecular species was a goal

mentioned by many Japanese researchers with whom I spoke, e.g., Dr. Aono of RIKEN, Dr. Tokumoto of NAIR, and Dr. Utsugi of NTT.

The main direction of the Electrochemiscopy project, though not completely determined at the outset, is similar to other ERATO projects in that it is organized around three groups: Interface structure group, interface formation group, and interface fabrication group. The STM will play a key role as an in-situ process diagnostic for the formation of highly ordered interfaces by chemical and electrochemical processes. At the time of my visit four of sixteen researchers have been hired, Dr. Yamada and three from SEIKO instruments, a Japanese STM manufacturer. Three or four of the remaining positions were to be filled by foreign researchers.

(iii) Nishizawa Terahertz Project

Facilities Visited:
- Terahertz Project, Sendai
- Semiconductor Research Institute, Tohoku University

Researchers:
- Prof. K. Suto and Dr. S. Suzuki

Topics Discussed:
- Perfect Crystal Project
- Photo-stimulated Molecular Layer Epitaxy
- Device Applications
- Silicon MLE

SUMMARY

Prof. J. Nishizawa, currently president of Tohoku University in Sendai, has led an extremely productive and successful university-industry collaboration in the area of device electronics called the Semiconductor Research Institute (SRI). The focus of SRI has ranged from power electronics, to microwave- and radio-wave electronics and, more recently, includes opto-electronic lasers and detectors for high-speed fiber-optic communication systems. These efforts have evolved over many years to include strong support from industry as sponsors and collaborators in commercializing many of these applications.

The Terahertz project is the second ERATO project awarded to Prof. Nishizawa. The first Nishizawa ERATO project, Perfect Crystal, has been completed. The terahertz frequency regime lies between the infrared and microwave regions of the electromagnetic spectrum. Fiber-optic and microwave communications have advanced because the materials and processing problems could be solved. The goal of this project is the development of methods which will allow the reliable fabrication of devices that operate in the terahertz region.

The Perfect Crystal project consisted of a materials group and three specific device groups

concerned with photo-sensor, thyristor, and integrated circuit applications. The materials aspect of that work, photo-stimulated molecular layer epitaxy (MLE) has been carried over and substantially enlarged in the new Terahertz Project. I met with Prof. K. Suto and Dr. S. Suzuki to visit the research facilities and discuss the project.

The MLE technique, also called atomic layer epitaxy, is a method which uses the chemical selectivity of gas-phase precursor molecules to achieve layer-by-layer growth of crystalline films of alternating compound semiconductor materials for opto-electronic components, such as laser diodes and detectors. By adding a light source which predissociates the reactant molecules into more highly reactive species, the Perfect Crystal project was able to obtain significant improvements in the performance of the devices made from this material. In addition to AlGaAs/GaAs heterolayers which was used in the initial devices, Prof. Nishizawa and his colleagues were able to demonstrate that the photo-stimulated MLE technique may provide significant improvements for silicon-, and II-VI compound semiconductor, epitaxy.

The facilities for this project contained perhaps a half-dozen research-oriented and dedicated production growth chambers. Photo-stimulated MLE is a powerful growth technique compared with MBE because the characteristics of the optical energy can be precisely controlled with respect to the arrival of precursor molecules at the surface. This permits the abruptness of the interfaces between heterolayers to be maintained and the optical and electrical properties of the device to be specified exactly.

3. Academic Facilities

(a) University of Tokyo

Facility Visited:
Department of Chemistry, University of Tokyo

Researcher:
Professor A. Koma

Topics Discussed:
Van der Waals Epitaxy (Heteroepitaxy)

SUMMARY

Prof. A. Koma of the Chemistry Department has been pursuing the concept of Van der Waals epitaxy for approximately seven years since his appointment at the University of Tokyo. Van der Waals epitaxy refers to the growth of highly ordered crystal lattices consisting of one type of material onto a crystal lattice of a second material. This is normally very difficult because imperfections on the growth surface, size effects, and lattice mismatch tend to destroy the periodicity of the crystal. By understanding and controlling the registry of the initial atomic

layer of one species onto the surface, Prof. Koma has shown that is possible to build layered structures of very heterogeneous materials. The goal of this research is to prepare structures with specific conducting, superconducting, insulating, or semiconducting properties.

Prof. Koma's group has explored this concept for a number of systems including LiF, MoS_2, GaSe, fullerenes, and organics. They have also pursued the use of passivation methods for semiconductor surfaces, such as hydrogen-passivated silicon and sulfur-passivated GaAs. The covalent nature of these technologically important materials induce bond formation between atoms on the free surface, so these passivation techniques are an important aspect of extending this potentially powerful technique to more widespread applications in nanofabrication technology.

(b) Tohoku University, Sendai

Facilities Visited:
- Institute for Materials Science (IMS)
- Super Clean Room (SCR) Facility

Researchers:
- Professors T. Sakurai and C. Park (IMS)
- Professor T. Ohmi (SCR)

Topics Discussed:
- STM Studies of Adsorbates on Silicon and Metal Surfaces
- Ultra Large-scale Integration (ULSI)
- Silicon Microroughness
- Plasma Etching
- Ion implantation
- μ-RHEED

SUMMARY

Prof. T. Sakurai has played a prominent role in Japanese research by establishing one of the earliest STM-based surface science laboratories in Japan at the Institute of Materials Science. He was also one of the first researchers to employ an STM coupled with a field ion microscope (FIM) for preparing and characterizing atomically sharp tips for high-resolution imaging. I spent my visit there discussing ongoing projects with Prof. C. Park, a visiting scientist from Jeonbug University in Korea. Prof. Sakurai has actively pursued collaborations with researchers from Russia, China and Korea, and spends a significant portion of his time in the United States at Pennsylvania State University.

Currently, Prof. Sakurai's group is using four identical FIM-STM systems. It was impressive to see three of them located in the same small, third-story labroom, along with the associated electronics and, perhaps, a half-dozen graduate students working away. This

approach, by avoiding the time-consuming process of constantly upgrading instrumentation at the expense of productivity, has allowed the students and visiting researchers to explore a wide-range of fundamental problems. Examples of this work include studies of adsorbates such as bismuth, sodium, cesium, silver and fullerenes on Si (111) and (100) surfaces and oxygen and fullerenes on single-crystal metal surfaces such as silver and copper.

In addition, efforts were underway to integrate a fourth FIM-STM with a GaAs MBE system, and I was told of plans to purchase a JEOL high-temperature STM.

The Super Clean Room is a dedicated clean room facility at Tohoku University which has been set up as a test bed for advanced silicon semiconductor processing and device fabrication. The idea for the facility was put forward by Prof. T. Ohmi and has been supported by an extensive network of industrial contacts. I met several foreign researchers from U.S. and European corporations during my tour of the facilities.

The present target for the Super Clean Room is ultra-large scale integration (ULSI), but many of the key challenges which arise in nanofabrication technology are being confronted here. These challenges include surface preparation, characterization of microroughness, effects of chemical impurities in gas and sample handling systems, water quality, and process control. Facilities such as the Super Clean Room, which systematically address these problems for ULSI, have considerable overlap with the ATP's generic technology theme, since reliable and reproducible investigation of nanostructures under realistic conditions cannot be realized otherwise.

Several important advanced processing principles have been demonstrated by this group; for example, Prof. Ohmi's group has employed scanned probe techniques to study the effects of water quality on the microroughness of silicon surfaces. The final etching and hydrogen-passivation of silicon wafers has been shown to be highly dependent on water quality, which leads to variations in the electrical properties of gate oxides grown on these surfaces. Plastic materials have been eliminated from all stages of the manufacturing process. Special polishing and passivation techniques for stainless steel chamber walls, valves, and gaslines have been implemented throughout the facility. A special frictionless gate valve was designed for use in a magnetic sample transfer system that reduces wafer contamination during through- vacuum transfers. This valve had been developed as a collaborative project with a manufacturer leading to a commercially available product, as have many of these projects.

I was impressed by efforts to refine or develop new processing and diagnostic instrumentation. For example, a double-electrode plasma etching instrument was under development. There are several practical advantages of plasma- type processing over other potential techniques. It is faster and in more widespread use than electron cyclotron resonance (ECR) etching, for example. The strategy of this new design allows both electrodes to be driven at shifted radio-frequency (RF) frequencies so that ion damage to the substrate can be greatly reduced. Ion damage during etching interferes with the electrical properties of devices and is becoming significant problem in scaling device structures to smaller dimensions. Other

examples include an ultraclean ion-implantation system with a UHV sample chamber, a coupled wet-chemical sample preparation chamber with contamination-free inert gas environment and sample transfer system was under development for routine use with existing etching, growth, and implantation instruments. I was also shown a prototype μ-RHEED system which had been developed in conjunction with the Shimadzu instrument company.

The success of the Super Clean Room must be due in large measure to the organizational skills of Prof. Ohmi. The laboratory seems to avoid the rigid task-setting which characterizes many of MITI's projects. In particular, the continual evolution of the facility to implement new technical advances seems to be a major goal of the facility. There are clearly lessons in this for nanotechnology.

The Super Clean Room facility and the Semiconductor Research Institute (SRI) involve at least 60 or so researchers and technicians as well as industrial collaborators. The size and success of these projects provide exceptions to the often-reported claim that barriers exist in Japan for collaboration between university researchers and industry.

B. CORPORATE RESEARCH AND DEVELOPMENT

1. Hitachi Ltd.

Facility Visited:
Hitachi Central Research Laboratory, Tokyo

Researchers:
Drs. S. Hosoki, S. Hosaka, and E. Takeda

Topics Discussed:
High-temperature STM Studies of Silicon Surfaces
STM Manipulation of Surface Atoms
Nanometer-scale Lithography
X-ray Lithography
Electron-beam Lithography

SUMMARY

I met with STM researchers Drs. S. Hosoki and S. Hosaka and with Dr. E. Takeda, a manager at the Nanometer Lithography Center, of Hitachi's Central Research Laboratory, Kokubunji. The STM group has developed a high-temperature UHV STM which they have used to carry out many detailed investigations of silicon surface growth modes. This microscope uses drift-correction algorithms to maintain the STM tip in the same position during high-temperature operation. More recently, Dr. Hosoki has demonstrated manipulation of indivdual surface atoms

of MoS_2 at room temperature and in air. Previously, such demonstrations were restricted to very low temperatures or UHV conditions. This work provides encouragement to those of us interested in the data storage potential of probe-based techniques.

Dr. Takeda discussed his company's current views concerning the most viable approaches to sub-micron lithography for ultra-large scale integration (ULSI). He emphasized the limitations of optical approaches and problems with proximity x-ray lithography. He seemed to believe that projection x-ray lithography for resist exposure was attractive, despite the severe technical challenges which remain to be solved in producing suitable optics, as is e-beam exposure, if breakthroughs can be obtained in that area.

2. NEC Corporation

Facilities Visited:
NEC Fundamental Research Laboratory, Tsukuba

Researchers:
Drs. S. Matsui, M. Baba, Y. Ochiai, T. Ide, P. Ajayan, and M. Kosaka

Topics Discussed:
Nanometer-scale Electron-beam and STM Lithography
Nanotube Characterization and Applications
Fullerene Characterization

SUMMARY

The Fundamental Research Laboratory of NEC in Tsukuba was perhaps the most impressive facility I had the chance to tour. The laboratory space was not only new and spacious, but the researchers seemed to be considerably younger and the atmosphere less formal compared with other Japanese corporate facilities. During my conversation with scientists there, it was mentioned that an attractive feature of NEC's approach is that each researcher has primary responsibility for at least one major piece of equipment through its design, operation, or collaboration with other groups.

I met with Drs. S. Matsui, M. Baba, and Y. Ochiai who have been investigating advanced electron-beam and STM-based techniques for nanotechnology. Dr. Y. Ochiai is using a 50-keV JEOL e-beam system to pattern 10-nm lines in resist and for e-beam assisted Cl_2 etching of GaAs. Dr. Baba has explored the low-voltage limit by using an STM tip as the excitation source for the etching reaction. Using the STM to measure a profile of the etched vs. unetched region of the surface, he has shown that this reaction is confined to the topmost monolayer or two of the GaAs surface.

I also spoke with Dr. T. Ide who described a UHV STM system he had built for surface

studies of silicon and growth interuption during GaAs MBE. I was particularly impressed with the apparently rapid design, construction, and testing cycles for this microscope. The technical support available for these projects is something that I did not have the time to investigate in detail.

The characterization and recent implementation of "nanotubes" by Dr. S. Iijima and his colleagues has received a great deal of attention within the scientific community. Nanotubes are an extension of fullerence chemistry, a very active area of nanotechnology. This group had recently reported making 5-nm wide, 200-nm long lead wires by using the nanotube as a casing.

I met with Dr. P. Ajayan a researcher on this project who emphasized the need for the unique array of state-of-the-art equipment available at NEC which made it possible to carry out these investigations in a reliable and timely manner. The facilities include a UHV-compatible high-reolution transmission electron microscope (TEM) and a number of dedicated, high-quality growth chambers for fullerenes. I toured the fullerene lab facilities with Dr. M. Kosaka who described the growth and characterization of doped C_{60}, as well as thin film MBE of fullerenes.

3. NTT Corporation

Facility Visited:
NTT Research Laboratory, Atsugi

Researchers:
Drs. Y. Utsugi, M. Tanimoto, and M. Tabe

Topics Discussed:
STM Manipulation and Lithography
STM/MBE Studies of GaAs Growth Processes
STM-based Potentiometry

SUMMARY

At the NTT laboratories in Atsugi, I met with Drs. Y. Utsugi, M. Tanimoto, and M. Tabe. The primary mission of this facility is to carry out basic research on semiconductors for communications applications, including silicon and compound semiconductor technologies. NTT became a quasi-private corporation in 1989, having been managed previously by the Ministry of Posts and Communications. As such, its researchers are unable to collaborate on MITI projects because of bureaucratic conflicts, at least in a direct way. This situation would seem to be unfortunate, since this laboratory, with its independent research environment, is engaged in projects which share considerable overlap with the ATP, for instance.

I discussed STM surface modification with Dr. Utsugi, one of the pioneers of this technique in Japan. His modification of AgSe surfaces using an STM built on his extensive experience

with thin films of this material for lithography. He emphasized his more recent interest in exploring layers of silver on silicon (111) surfaces as offering a more controlled substrate for STM surface modification, and has spent considerable time investigating such important topics for STM-based nanofabrication technology as whether raster scan is better than vector scan techniques for the STM. (His results indicate that raster scan is better.)

In Dr. Utsugi's opinion, it is essential to develop STM characterization techniques as an integral part of STM nanofabrication, an opinion which I share from my own research.

My visit to Dr. Tanimoto's lab included a discussion of two systems his group constructed which combine STM analysis with MBE growth: The first system, in operation for some time, consists of an Omicron UHV STM coupled to a research-type MBE system for studying GaAs, InGaAs, and AlGaAs heterolayer growth. He emphasized the advantages of in-situ STM, and mentioned that the tremendous vibrational stability of the Omicron STM made it possible to obtain atomic resolution STM images even with the MBE turbo-pumps and liquid nitrogen lines operating. The second system combines a metallorganic MBE growth chamber with a JEOL 4500VT STM for investigating the step-edge growth of nickel/aluminum quantum wires. Dr. Tabe, who is involved in silicon nanodevice research, collaborated with Dr. Tanimoto on a project that employs STM spectroscopy to characterize ultrathin oxide layers on silicon surfaces. This knowledge is important for their performance as tunnel barriers in quantum electron devices. This is another example of how the considerations of fabrication and characterization become truly interdependent at the nanometer scale.

4. JEOL Ltd.

Facilities Visited:
JEOL Production Facility, Tokyo

Researcher:
Dr. M. Iwatsuki

Topic Discussed:
JEOL Variable-temperature STM

SUMMARY

I met with Dr. M. Iwatsuki, the principle design engineer of the JEOL variable-temperature STM, 4500VT. The most notable feature of this unique instrument is that it is capable of drift-free operation over a temperature range of 30 K to 1200 K. Achieving atomic resolution over a range of temperatures is difficult with STM because thermal expansion of the various STM component materials occurs at different rates. Relying on previous experience gained during the design of superconducting lens systems for their electron microscopes, JEOL engineers have been able to solve this problem.

By working closely with STM researchers, JEOL has produced an instrument which meets the needs of their prospective customers, primarily surface and materials scientists. The system, for example, has provisions for implementing in-situ UHV surface preparation methods. An optional UHV-compatible electron gun is available for observing surfaces by scanning electron microscopy (SEM), an obvious accessory for a SEM company to provide. It is interesting to compare this successful approach with that of other SEM manufacturers who have offered STMs as an option on their commercial SEMs. Since STM surface requirements are generally incompatible with the poor vacuum conditions of typical SEMs, the research potential is limited. Despite the high cost of this instrument (approximately US$ 300-400K), I was told that orders for over two dozen systems have been received. The 4500VT STM was installed at several of the laboratories I visited in Japan: ETL (Dr. Tokumoto), Aono (Dr. Grey), NTT (Dr. Tanimoto), and RIKEN (Dr. Aoyagi).

III. THE ORGANIZATION OF PUBLIC-SECTOR R&D IN JAPAN

The key to understanding MITI's major investment in nanotechnology, the structure of NAIR and the ATP, and the involvement of such a large base of corporate R&D members in this effort lies in the organization of public-sector R&D in Japan. Here I describe some of the most significant elements of this organization which appear to me to be relevant for understanding nanotechnology in Japan.

A. MITI's Large-scale Projects

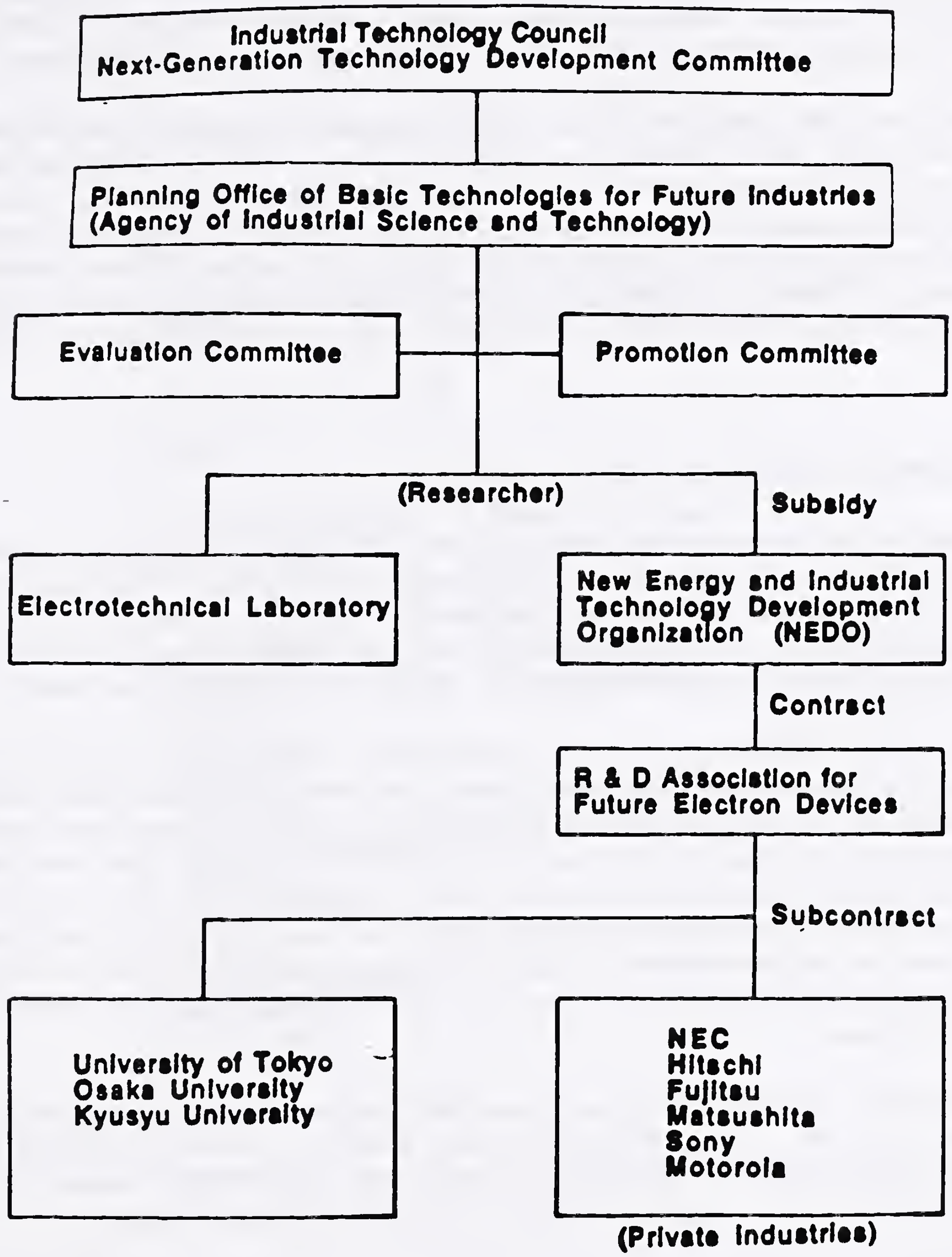
Japan's rise to global preeminence in advanced manufacturing methods and MITI's role in it are familiar enough to need no further comment. The mechanism established to carry out this effort developed out of unique historical circumstances and a highly cooperative relationship between government and industry[6]. These factors have produced a public-sector R&D funding structure which functions in a manner which is considerably different than that in the US.

Traditionally, the goal of MITI's effort was to target R&D in narrowly selected technology areas. These efforts were aimed at improving the global competitive stance of specific Japanese industries, particularly the "knowledge industries". These efforts have been undertaken in a highly formalized process which culminates in the the establishment of a fixed-term research project. The structure of these projects tends to follow a rigid pattern; a typical example is illustrated by the organizational chart for the Quantum Functional Devices Project shown in TABLE IV. The general features of this approach are described below.

The goals and activities of the project are specified completely prior to project initiation. One of the most notable features of this process are that major corporations play several roles: (a) as advisors to MITI during the proposal, planning, and execution stages of these projects; (b) as contributors to the project, usually providing some mixture of research facilities and personnel in addition to direct financial support; and, (c) as the ultimate beneficiaries of these projects.

The decision to proceed with a specific research project is made by MITI agencies, led by the Agency for Industrial Science and Technology (AIST), following several rounds of planning committee meetings, and occasionally workshops involving advisory groups of government, academic industrial researchers and managers from corporate R&D departments. (The top two blocks of TABLE IV). Once the decision to fund the project is made, an R&D association with formal legal standing is assembled. This entity undertakes legal and financial dealings with MITI's New Energy and Industrial Technology Development Organization (NEDO). (Right hand side of TABLE IV.) The association is often a multi-tiered entity made up of six to ten corporations within the relevant industrial sector; typically, only a small number of the largest corporate participants contribute the facilities and personnel required to perform the actual research. The remaining members contribute dues in exchange for access to research results. During the planning phase, a project leader from a government office or laboratory such as the

TABLE IV. ORGANIZATION OF QUANTUM FUNCTIONAL DEVICE PROJECT



Electrotechnical Laboratory is chosen. (Left hand side of TABLE IV.) The project leader's role involves coordinating activities between MITI agencies, the corporate researchers, and the R&D association. Through agreements with the association, the overall project is broken into distinct subproject areas, typically three. It appears that the activities which comprise the subprojects are free-standing and usually no effort is made during any stage of the project to synthesize the results into a more coherent technological basis. This is probably intentional, in order to discourage unfair competitive arrangements from developing among the active participants.

These results are disseminated initially through reports and at meetings held semi-annually with the time-advantage of this research benefitting primarily the company doing the work, followed by the other members of the consortium. This system works because of the "assistance" of MITI's Industrial Bureaus in securing the participation of a sufficient number of industrial concerns. These bureaus appear to hold considerable leverage in their respective economic sectors. Government or university researchers sometimes provide research support in addition to their role in advising AIST, (as indicated in the lower left hand side of TABLE IV).

B. Evolutionary Potential of MITI's Approach

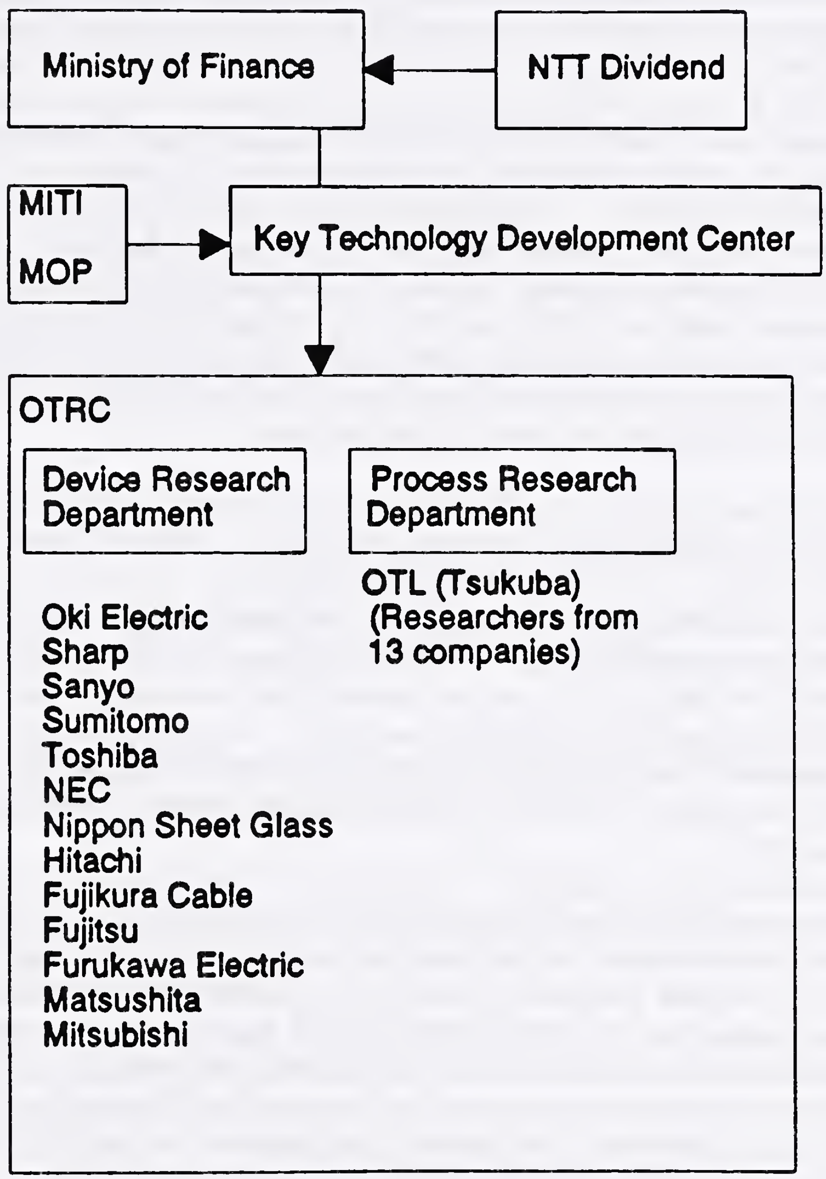
The network of fixed term projects, advisory panels, R&D associations, and semi-annual meetings has traditionally spread the costs of R&D among a broad range of large and small companies, which may or may not realize a direct benefit. Indirectly, of course, it is a form of corporate taxation which is intended to benefit ultimately the overall economy. A somewhat similar example from past U.S. history might be the funding of Bell Laboratories' research.

This network which MITI has evolved is a much more valuable resource for the current situation, however. Not only does it allow new ideas to be investigated and evaluated without establishing permanent laboratory facilities and positions, but it has the extremely useful benefit that it encourages program managers and researchers within participating institutions to be more outward looking and responsive to novel research ideas. Over time, the various corporate, government, and academic participants and their organizations learn to work in a much more flexible mode than they might otherwise. It appears that an important element for the success of these projects is that the corporations have input into future projects through the workings of the planning committees.

The AMMTRA and QFD projects are examples of MITI projects organized in the traditional style. The mission of the Optoelectronics Technology Research Laboratory (OTL) project represents a significant contrast to these projects. Specifically, it signals MITI's exploration of an appropriate mechanism for engaging in research of a more fundamental nature.

Support for the OTL project arose from a combination of events: First, experience gained during previous very large scale integration (VLSI) and optoelectronics programs, ca. 1976-1980 and 1979-1986, indicated a rigid, corporate-based research strategy would not work for problems

TABLE V. ORGANIZATION OF OPTOELECTRONICS TECHNOLOGY RESEARCH



requiring a high degree of research integration, and, second, that a large amount of funding from the privatization of the telephone company, NTT, became available.[7] This led to the creation of an Optoelectronics Technology Research Corporation (OTRC) consisting of thirteen companies, organized under the formal direction of MITI and the Ministry of Posts (MOP), which ran NTT prior to divestiture, as shown in TABLE V.

The charter of the Key Technology Development Center set up a novel, dedicated research facility for investigating fundamental processing issues of compound semiconductor materials in addition to the device-oriented R&D which was to be done, as before, at corporate facilities. This marked the first attempt by MITI to bring together corporate researchers from competing companies so that they could work closely on basic processing issues. Furthermore, decisions concerning the project goals and technical direction were to be left largely to OTL managers rather than decided ahead of time. My impressions of how these policies have affected the working environment at OTL are quite favorable. The physical layout of the experimental apparatus seemed to encourage a greater degree of interaction among the researchers and less of a sense of isolation which sometimes engulfs large research facilities engaged in diverse problems; generally, I had the sense that OTL somehow struck the right balance of scope, direction, and execution. It will be interesting to see what MITI does with OTL, and the experiences gained from this project, when it ends this year.

C. The Future: MITI's Atom Technology Project

The networks of academic, government, and corporate advisors which effectively set MITI's technical direction reflect a broad range of scientific and corporate influences. These networks act as an important feed-back mechanism for shaping new directions in public-sector R&D funding, through their planning and evaluation activities. This influence has had a significant impact on the directions of MITI projects as public-sector R&D becomes less concerned with advanced manufacturing technology and more concerned with finding a role for itself in basic science and technology.

The underlying cause for this shift was that corporate R&D capacity over the last decade had become sufficient for new product innovations, i.e., those which may be three to five years away, at least for the top-tier companies. This meant that MITI's traditional approach might now interfere with, rather than assist, the development of these innovations. The logical result was for MITI to focus on more fundamental research directions, ten-plus years away, without losing sight of its primary mission to industry. The emergence of nanotechnology during the 1980's was particularly favorable, and quickly recognized by researchers from academic, government, and corporate labs as a tremendous opportunity.

The first English-language document outlining the concept of the Atom Technology Project (ATP), with which I am familiar, is dated June 1989. Already at this stage, the key technical ingredients consisting of three-dimensional control of gas-phase atoms, surface manipulation, generic technology, and theoretical methods had been identified. This means that at least four

years were required to complete the remaining planning and funding decisions.

A look at the resulting organizational chart of the ATP, TABLE VI, reveals that the elements used by MITI in setting up a free-standing research facility for the Optoelectronics Technology Research Laboratory (OTL) appear here also, called the ATP Research Body. In addition to corporate researchers, the ATP Research Body includes researchers recruited from government laboratories such as the Electrotechnical (ETL) and the Metrology Labs in Tsukuba. Of the seven initial ATP research groups, three are to be led by project leaders from ETL, three from industry, and one from academia.

The involvement of private companies at the time this report was written is remarkable: There are over fifty members of the R&D association, several of which are Japanese subsidiaries of US corporations, e.g., Texas Instruments and Motorola. The association is a three-tiered structure with a handful of the major Japanese corporations contributing most in terms of resources, including dues and personnel. Given the budget and the term of this project, it appears that members of the R&D association may have had some concerns about the direction of the project. The project leader, Dr. Maruyama, resigned his position as a former director of research at Hitachi in order to officially represent the government in the operation of the ATP Research Body.

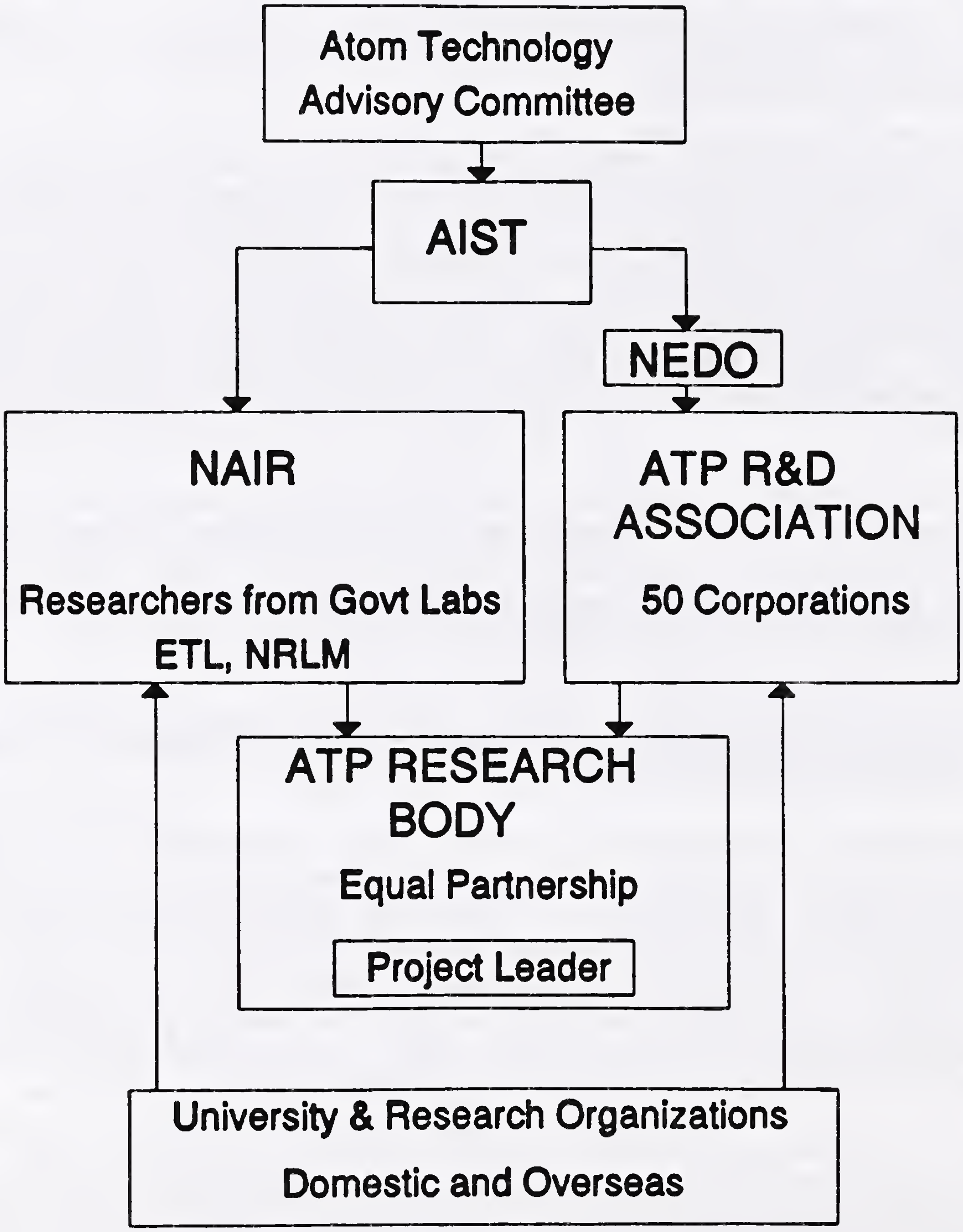
One of the most significant components of the ATP is the specific involvement of overseas research organizations, however. Although there are many individual US and European postodoctoral researchers and visiting scientists at MITI facilities in Japan, these are very different policies. The STA's recognition of, and success with, international collaboration as an essential element of its ERATO and RIKEN programs is clearly in evidence here.

D. MITI Projects Contrasted with Those of the Ministry of Education and the Science and Technology Agency

MITI projects are, by no means, the only source of funding for investigating nanofabrication technology in Japan. The Ministry of Education (MOE) and the Science and Technology Agency (STA) support vigorous efforts, as illustrated by the examples presented in Section II. The emphasis of these programs naturally favor more fundamental research, but, because many academic researchers are involved in MITI's networks through their input on planning and advisory committees, the attitudes fostered by these agencies have important significance far beyond academic circles. This is particularly evident in the case of an area such as nanotechnology, with its focus on integrating basic and applied research.

Much has been made of the neglect of research facilities at universities in Japan. The priorities of the MOE are influenced, to a considerable extent, by its comprehensive educational function for the nation. The vast majority of scientists and engineers produced by the universities are destined for careers in corporate R&D, manufacturing or management in one of the major industrial companies. Research, as an element of an advanced technical education,

TABLE VI. ORGANIZATION OF THE ATOM TECHNOLOGY PROJECT



represents only small part of the MOE's overall concern, in contrast to the NSF in the United States. Academic research groups are directed by a few professors who have enormous authority within the university, according to the German system. However, their positions and normal funding are guaranteed without regard to merit or the productivity of their research. This limits the size of even very active research groups to 3-4 "permanent" research associates, several postdocs, and a few remaining graduate students, and presents few opportunities for researchers to engage in independent scientific pursuits.

An important element in the efforts to change the situation at university laboratories is the MOE's programs to select Distinguished Researcher and Priority Area Research Projects for special funding and recognition. This funding is highly sought after, since it provides for deeper, more systematic investigation of novel scientific ideas than is generally possible otherwise in Japanese research. In the Priority Area projects, for example, the project leader may subcontract a considerable portion of the research out to other university professors in order to increase the breadth of topics to be covered.

This situation might improve somewhat if MOE policies did not discourage academic researchers from collaborating with industrial and government laboratories. I came across instances where I was told that this has been a problem, but several researchers I spoke with also mentioned that things are beginning to change. In any event there are exceptions; the most dramatic examples of outstanding university-industrial collaborations that I experienced were Professor Nishizawa's role in the Semiconductor Research Institute and Professor Ohmi's Super Clean Room Facility, both at Tohoku University in Sendai. Presumably, being located outside of Tokyo makes this easier to accomplish.

Japan's Science and Technology Agency (STA) is organized under the Prime Minister's office. Its primary mission, in contrast to the more comprehensive roles which MITI and ME play in Japanese society, is concerned exclusively with the promotion of fundamental scientific research and technology in Japan. Because of this narrower focus, it has successfully identified and taken steps toward implementing the major ingredients needed to to establish Japan as a recognized leader in scientific research. These have become trademarks of its ERATO and RIKEN Frontier Research programs.

The STA seems to have recognized some time ago that there are two essential components of basic research. First, basic research requires opportunities for researchers to explore broadly defined research areas with considerably more the independence and self-motivation than had been available previously within the traditional Japanese consensus system. Second, Japanese facilities and programs must be managed in such a way that they provide a research environment which is suitable for fostering international collaborations.

The ERATO projects require the project leader, who is otherwise given almost complete freedom to define the scope and direction of the project, to recruit a certain fraction of non-Japanese researchers for the five-year term of the project. This is normally about one third of the total number hired.

The execution of the project, since it depends on the prior resources and managerial abilities of the project leader, reflects this researcher's personality. There are great differences in the focus and deployment of personnel and equipment, for example, between Prof. Nishizawa's Terahertz project, which builds on the previous Perfect Crystal project and extensive SRI facilities, and Dr. Aono's Atomcraft project which is being carried out in seemingly physically isolated facilities in Tsukuba. This unusual sense of opportunity for researchers in Japan has generated tremendous respect and interest for these researchers, especially in within the Japanese scientific community.

The Frontier Research Programs at RIKEN are also at the forefront of the STA's efforts to cultivate an international research environment in Japan. The sense of place at these facilities were perhaps the least "Japanese" of all that I visited. According to discussions with Drs. Knoll and Sasabe, RIKEN has been able to provide living quarters nearby for most of the foreign researchers who make up approximately one third of the staff of five hundred.

IV. IMPLICATIONS OF JAPAN'S COMMITMENT TO NANOSCALE SCIENCE AND TECHNOLOGY

As described in Section III, MITI is being transformed into an organization with increasing responsibility for promoting fundamental research. Through its advisory networks, it has identified nanotechnology as a discipline for which its infrastructure is ideally suited. This transformation of MITI over the next decade should be of great interest to policy makers, program managers, and researchers in the United States since it can yield valuable lessons about the organization of the scientific enterprise.

This transformation of MITI is occurring in Japan just as U.S. funding agencies are re-evaluating their own missions, with much debate centering on the creation of effective technology transfer mechanisms. Indeed, recent U.S. efforts to derive benefit from its huge investment in basic research, such as NIST's highly regarded Advanced Technology Program (also referred to as ATP), appear to be complementary to MITI's direction.

There may be opportunities for both the United States and Japan in this situation, as the goals of cooperative basic research and industrial competitiveness become bound together in the pursuit of nanotechnology. In particular, Japan has clearly identified its needs by recognizing international collaboration, involving both individual researchers and institutions, as an essential part of MITI's ATP structure. Once this project is fully underway, perhaps by mid-1995, domestic Japanese and foreign corporate R&D association members and universities will interact regularly with the international research body at NAIR. The U.S. R&D community, through involvement in this complex experiment, may benefit by adopting an organizational approach which is more appropriate for the integration of fundamental R&D into advanced manufacturing technology.

There are several potential difficulties which MITI's ATP must carefully avoid as it strives for international recognition in nanotechnology over the next decade: First, prior success with its large-scale industrial R&D projects does not necessarily ensure its success in promoting basic science, since cultivation of fundamental research is a very different matter. It is not entirely clear at this time how certain aspects of MITI's programs, such as traditionally rigid goal-setting and a lack of synthesis of research results, might interfere with opportunities for original thinking and self-motivation. For example, I expect that a cross-disciplinary synthesis of the research output of NAIR research groups (see page 21) must become a recognized benchmark fairly early on for the ultimate success of MITI's ATP program.

Second, a true international research presence at NAIR is one of the goals of the ATP. However, U.S.-Japan programs for postdoctoral study in Japan have not attracted a sufficient number of candidates to fill the available positions, according to the NSF-Tokyo Office which has coordinated nearly all exchange programs. Several reasons have been advanced to explain this, but it appears to be related to a lack of endorsement on the part of university thesis advisors and postdoctoral fellows, who typically have less direct personal experience or familiarity with research in Japan. This is not likely to change until Japanese research institutions succeed in

involving a larger number of senior U.S. researchers. The institutional links which are being established within the ATP may improve the situation, but will require considerable time and effort on the part of Japanese researchers.

In conclusion, there is considerable activity in the area of nanofabrication technology in Japan. The public-sector funding mechanism in Japan, especially through MITI's network of academic, government, and corporate research advisors and its project-oriented R&D strategy, is in a unique position to recognize and contribute to the fundamental knowledge base of this emerging discipline. Careful attention to progress made by programs such as MITI's ATP over the next decade is likely to provide valuable insight into how nanotechnology research can be effectively coupled to advanced manufacturing in the next century.

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